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FREQUENCY OF DENSE AND THICK FOG IN CENTRAL LONDON AS COMPARED WITH FREQUENCY IN OUTER LONDON

By J. H. BRAZELL, M.Sc.

Summary.—Tables are given comparing fog frequencies for central London (Kingsway) with those for outer London (Kew, Heathrow and Croydon) over a period from 1947 to 1962. In general, it was confirmed that dense and thick fog occurred less frequently in central London than in the suburbs because of the heating effect of the heavily built-up area. The dates of the introduction of smoke control in various boroughs indicate that smoke abatement may be a factor contributing to the marked decrease in the frequency of dense fog in central London over the period.

Introduction.—By international agreement fog is defined as visibility below 1100 yd but, in general, it does not become a major hindrance or nuisance to the public until the visibility falls below 220 yd. Therefore, discussion in this note is confined to thick fog, defined as visibility less than 220 yd, and dense fog, defined as visibility less than 55 yd. In 1938 Bilham[1] pointed out that during foggy weather visibility is often better in the centre of a large city than it is in the adjacent suburban and rural districts, and he attributed this effect to the fact that large buildings in a built-up area act as a source of heat and tend to reduce radiation from the ground. In 1959 Shellard[2] showed that the frequency of visibility below 220 yd, during the decade 1947–56, was less at Croydon than it was at Kingsway, but that the Kingsway frequency was much less than the frequency at either Kew or London (Heathrow) Airport. The object of this note is to examine the relative frequency of dense and thick fog in central and outer London in more detail and over a longer period than was done by Shellard.

Data.—Table I gives the annual number of hours of dense and thick fog at Kingsway, London (Heathrow) Airport and Kew during the 16-year period 1947–62 and at Croydon during the 12 years 1947–58. The frequencies for Heathrow (1947–62) and Croydon (1947–56) are based on hourly observations but the Kingsway figures (1947–62) are based on 3-hourly observations only, assuming, as Shellard did, that each observation represents 3 hours of fog in the same range. Doubts may be expressed about the validity of this assumption, but Kelly[3] has shown that the error introduced by using 3-hourly observations to estimate the total number of hours of persistent fog is an over-estimation of only about 4 per cent, and Shellard has demonstrated that

TABLE I—ANNUAL NUMBER OF HOURS OF DENSE AND THICK FOG AT KINGSWAY, LONDON (HEATHROW) AIRPORT AND KEW 1947–62, AND AT CROYDON 1947–58

	Annual number of hours of fog							
	Kingsway		Heathrow		Kew		Croydon	
Year	Dense	Thick	Dense	Thick	Dense	Thick	Dense	Thick
1947	24	81	48	195	84	180	21	61
1948	36	126	61	263	126	300	90	175
1949	15	51	61	206	156	282	3	65
1950	30	57	52	164	138	234	16	65
1951	12	51	55	163	78	234	40	117
1952	75	99	88	193	102	204	38	111
1953	24	69	77	337	54	396	44	177
1954	3	12	12	96	24	102	16	43
1955	6	33	29	152	42	102	15	54
1956	27	90	68	206	84	198	39	122
1957	9	27	40	120	54	126	18	42
1958	9	36	51	243	54	258	72	312
1959	21	99	98	254	132	270		
1960	6	27	21	110	24	132		
1961	0	27	40	147	24	144		
1962	30	78	84	183	174	282		
Period	Average annual number of hours of fog							
1947–50	26	79	55	207	126	249	33	91
1951–54	29	58	58	197	65	234	35	112
1955–58	13	47	47	180	59	171	36	133
1959–62	14	58	61	173	89	207		
1947–56	25	67	55	197	89	223	32	99

Note: Heights above mean sea level are: Kingsway 65 feet, Heathrow 80 feet, Kew 18 feet, Croydon 217 feet.

a very good estimate of annual fog frequency can be obtained from 6-hourly observations. Using the method adopted by Shellard, the annual frequencies of thick and dense fog at Kew, and at Croydon during the years 1957 and 1958 were obtained from the available fog frequencies for the four hours 0300, 0900, 1500 and 2100 GMT published in the annual summary to the *Monthly Weather Report.** (The 0300 GMT fog frequencies for Kew, and for Croydon during the year 1958 were not available and had to be estimated by multiplying the appropriate 0900 GMT frequencies by the ratio between the 0300 and 0900 GMT frequencies for Heathrow in the case of Kew, and South Farnborough in the case of Croydon.) It must be pointed out that the frequencies of dense fog at Kew for the period 1949–62 and at Croydon for the years 1957 and 1958 refer to visibility below 44 yd.

Table II shows that the 1947–56 average annual frequencies of dense and thick fog at Heathrow and Croydon, based on hourly observations, agree very well with Shellard's frequencies which were based on observations at the four standard hours 0300, 0900, 1500 and 2100 GMT. The reason for the slight variation in the figures for Kew is that Heathrow observations were used to estimate the Kew 0300 GMT frequencies for this article whereas Shellard used the Croydon observations. It is considered that Heathrow is more representative than Croydon of conditions at Kew. Allowing for the different visibility

* Meteorological Office. *Monthly Weather Report. Summary for the Year.* London, HMSO.

TABLE II—COMPARISON OF TABLE I FIGURES FOR 1947–56 WITH PREVIOUS WORK

	Kingsway		Heathrow		Kew		Croydon	
Visibility in yards, less than	55	220	55	220	44	220	55	220
	Average annual number of hours of fog							
1947–56 (See Table I)	25	67	55	197	89	223	32	99
Visibility in yards, less than	44	220	44	220	44	220	44	220
	Average annual number of hours of fog							
1947–56 (See Shellard[8])	19	126	46	209	79	213	25	104

limits used and the slightly different period, the average annual frequency of dense fog at Kingsway during the decade 1947–56 agrees with that given by Shellard, but there is a marked disagreement in the frequency of thick fog. The frequency quoted by Shellard is based on information extracted from the Kingsway observation registers by an outside body. A comparison of the information extracted by this unit with the observation registers showed that, presumably because of a misunderstanding of the visibility code, they had included a large number of occasions of visibility equal to 220 yd (or between 220 yd and the next higher limit) in their frequencies of visibility below 220 yd for the period 1947–54. As a result the 1947–56 average annual frequency of visibility below 220 yd given by Shellard is much too high.

Discussion.—Table I shows that in every year from 1947 to 1962 the frequency of dense fog, and of thick fog, was less at Kingsway than it was at either Heathrow or Kew. During the period 1947–58, the frequency of thick fog at Kingsway was less than it was at Croydon in 11 years out of 12, and Kingsway had less dense fog than Croydon in 8 years out of 12. The lower frequency of dense and thick fog at Croydon compared with Heathrow and Kew is probably due to Croydon's higher altitude. It is interesting to note that, apart from a slight increase in the frequency of dense fog at Kingsway and Heathrow between 1947–50 and 1951–54, the 4-year means (Table I) show a continual decrease in the frequency of dense and thick fog at Kingsway, Heathrow and Kew during the period 1947–58 compared with a steady increase at Croydon.

Table III gives the average annual frequencies of dense and thick fog at Kingsway, Heathrow and Kew for the two 8-year periods 1947–54 and 1955–62. Comparison of these two 8-year means shows a decrease in the frequency of

TABLE III—AVERAGE ANNUAL NUMBER OF HOURS OF DENSE AND THICK FOG AT KINGSWAY, HEATHROW AND KEW DURING 1947–54 AND 1955–62 AND THE PERCENTAGE DECREASE

		Average annual number of hours of fog 1947–54	1955–62	Decrease *per cent*
Dense fog	Kingsway	27	13	52
	Heathrow	57	54	5
	Kew	95	73	23
Thick fog	Kingsway	68	52	24
	Heathrow	202	177	12
	Kew	241	189	22

thick fog of 24 per cent at Kingsway, 22 per cent at Kew and 12 per cent at Heathrow. However, the decrease in the frequency of dense fog is 52 per cent at Kingsway compared with 23 per cent at Kew and only 5 per cent at Heathrow. The lower frequency of fog in the centre of London, compared with the outskirts, is attributed to the heating effect of the heavily built-up central area, but it is extremely unlikely that an increase in this heating effect was the reason for the marked decrease in the frequency of dense fog at Kingsway for the period 1955–62.

Comparing the two 8-year periods 1947–54 and 1955–62, Table IV shows that there was no change in this heating effect during the winter 6 months as measured by the difference in mean temperature between St. James's Park and Heathrow, while the difference in mean temperature between Kingsway and Heathrow displayed an apparent decrease in the heating effect. However, the Kingsway observation site was moved in September 1959 from the roof of Victory House, where the thermometer screen was located in the centre of a cluster of buildings, to the roof of Princes House where the screen was placed on the edge of the building overlooking Kingsway. This change of site may be the main reason for the apparent decrease in the heating effect.

TABLE IV—COMPARISON OF MEAN TEMPERATURES FOR TWO 8-YEAR PERIODS

	Jan.	Feb.	Mar.	Oct.	Nov.	Dec.	Average of the six months
				degrees Fahrenheit			
1947–54							
Heathrow	39.4	39.2	44.0	52.0	45.2	41.7	43.6
St. James's Park	40.6	40.3	44.9	53.3	46.2	43.0	44.7
Kingsway	42.4	41.6	46.0	54.2	48.3	44.9	46.2
Difference (St. James's Park—Heathrow)	1.2	1.1	0.9	1.3	1.0	1.3	1.1
Difference (Kingsway —Heathrow)	3.0	2.4	2.0	2.2	3.1	3.2	2.6
1955–62							
Heathrow	39.5	40.1	44.0	52.5	44.8	40.9	43.6
St. James's Park	40.6	41.0	45.0	53.6	46.0	42.2	44.7
Kingsway	42.0	42.1	45.6	54.4	47.1	43.7	45.8
Difference (St. James's Park—Heathrow)	1.1	0.9	1.0	1.1	1.2	1.3	1.1
Difference (Kingsway —Heathrow	2.5	2.0	1.6	1.9	2.3	2.8	2.2

The marked decrease in the frequency of dense fog at Kingsway compared with Kew and Heathrow may be due to a decrease in smoke pollution in the centre of London; 65 per cent of the observations of dense fog at Kingsway during the period 1947–62 were associated with calm conditions, and the wind was only 1 knot or less on 77 per cent of the reports of dense fog, which suggests that locally produced pollution may be more important than drifting pollution from outside the centre of the city. In this connexion, two factors must be considered, namely population changes and smoke control. During the post-war years many people have moved from central to outer London but the estimated decrease in population from 1947 to 1960 was only 4 per cent in the region within 2 miles' radius of Kingsway and only 3 per cent in the region within 4 miles. This slight decrease in population would probably have little effect on smoke pollution. The power to control smoke was given to local authorities in the Clean Air Act of 1956, but the City of London already possessed this power under the City of London (Various Powers) Act of 1954.

Table V gives the date when smoke control commenced, and the percentage number of premises and dwellings covered by smoke control at the end of 1958, 1961 and 1962 for the Local Authorities within a 3-mile radius of Kingsway, Kew and Heathrow. In the case of Local Authorities who only partly fall within one of these circular areas, a rough indication of the percentage of the borough or district within the area is given in Table V, but Local Authorities with less than a quarter of their region within one of the circular areas have been excluded. Table V shows that, in general, smoke control commenced earlier and progressed faster in the regions around Kingsway than it did in the regions around Kew and Heathrow. Kingsway is situated near the boundaries separating the City of London, Westminster and Holborn; the City was a smokeless zone by October 1955 and smoke control commenced in October 1958 in Westminster and in September 1959 in Holborn, so that by the end of 1962 Holborn and about 40 per cent of Westminster were also smokeless zones. Kew is situated in the borough of Richmond close to the boundaries with the boroughs of Twickenham and Heston and Isleworth; in two of these boroughs smoke control commenced in 1960 but in Twickenham it did not commence until May 1961. By the end of 1962, only 25 per cent of Richmond,

TABLE V—PROGRESS OF SMOKE CONTROL IN GREATER LONDON

Local authority	Smoke control commenced	Percentage number of premises and dwellings covered by smoke control by:		
3-mile radius of Kingsway	*date*	*end of 1958*	*end of 1961*	*end of 1962*
City of London*	1 Oct. 1955	100	100	100
Holborn	1 Sept. 1959	nil	71	100
Westminster	1 Oct. 1958	1	17	41
Southwark	1 Nov. 1961	nil	5	11
Lambeth (40)†	1 Oct. 1959	nil	3	8
St. Marylebone	1 Oct. 1958	8	53	67
St. Pancras (70)	1 Sept. 1959	nil	11	11
Finsbury	1 June 1962	nil	nil	9
Shoreditch	1 Sept. 1959	nil	18	37
Bethnal Green (60)	1 Dec. 1960	nil	33	62
Stepney (45)	1 Nov. 1960	nil	9	20
Bermondsey (55)	1 Oct. 1958	1	11	27
Chelsea (70)	1 Nov. 1960	nil	21	41
Paddington (50)	31 Oct. 1959	nil	18	33
Islington (60)	1 Sept. 1960	nil	4	8
3-mile radius of Kew				
Richmond	1960	nil	2	25
Twickenham (45)	9 May 1961	nil	nil	6
Heston and Isleworth (60)	1 Oct. 1960	nil	8	14
Ealing (25)	1 July 1960	nil	11	20
Brentford and Chiswick	1 May 1960	nil	12	12
Barnes (75)	1 Nov. 1961	nil	12	22
3-mile radius of Heathrow				
Feltham (75)	1 Nov. 1961	nil	14	20
Staines (45)	1 Dec. 1960	nil	18	26
Yiewsley and West Drayton (90)	1 Dec. 1960	nil	19	37
Hayes and Harlington (55)	1 June 1958	1	39	51
Heston and Isleworth (45)	1 Oct. 1960	nil	8	14

*The Port of London is not a smokeless zone, but "The Dark Smoke (Permitted Periods) (Vessels) Regulations" have been applied since 1 June 1958.

†The figures in brackets in the first column are the approximate percentages of the boroughs or districts within the 3-mile radius.

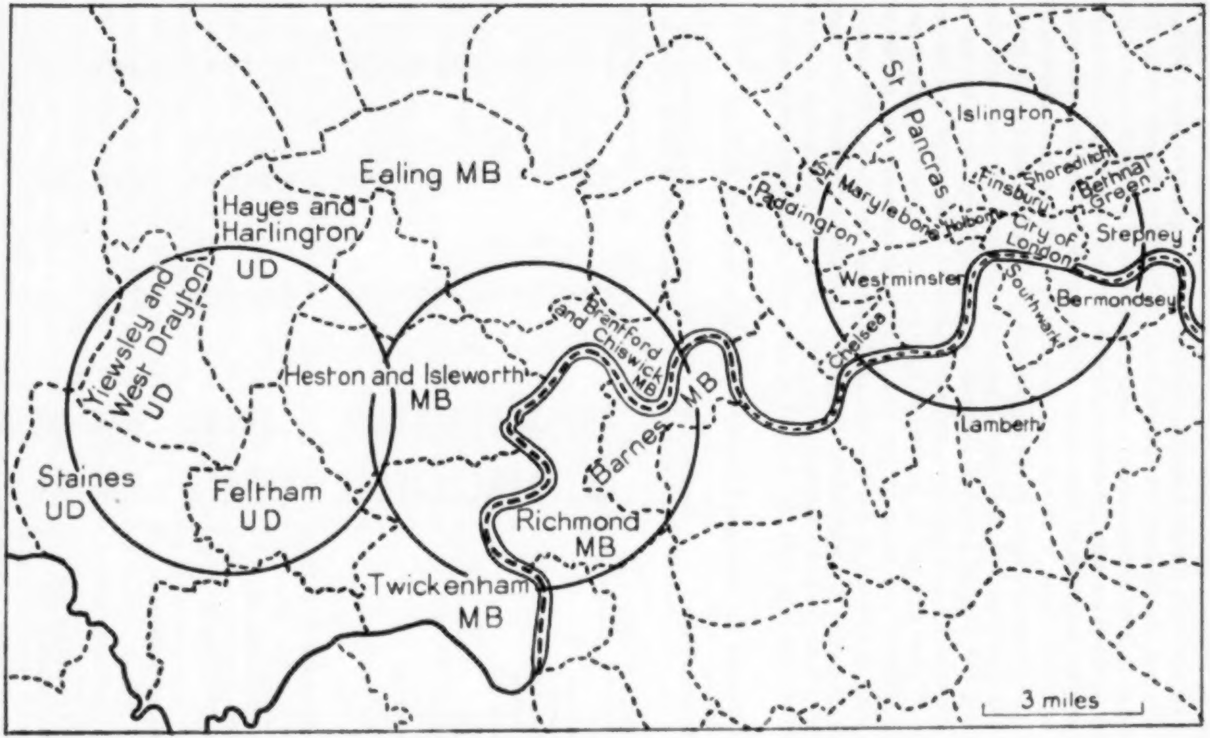

FIGURE 1—LOCATION OF AREAS MENTIONED IN TABLE V

Circles show the 3-mile radius areas round (left to right) Heathrow, Kew and Kingsway

14 per cent of Heston and Isleworth, and 6 per cent of Twickenham were covered by smoke control. Heathrow is in Yiewsley and West Drayton close to the boundaries with the urban districts of Hayes and Harlington, and Feltham; smoke control commenced in December 1960 in Yiewsley and West Drayton, in June 1958 in Hayes and Harlington, and in November 1961 in Feltham. By the end of 1962, smoke control applied to 37 per cent of Yiewsley and West Drayton, 51 per cent of Hayes and Harlington and 20 per cent of Feltham. It is clear that progress in smoke abatement has been substantially greater in the Kingsway area than it has been in the regions around Kew and Heathrow, and this may have been a contributory factor to the marked decrease in the frequency of dense fog at Kingsway for the period 1955–62. Figure 1 shows the location of areas mentioned in Table V.

However, dense persistent fog still occurs in central as well as in outer London. The last persistent fog was in December 1962, and it is interesting to compare the frequency of dense and thick fog at Kingsway and Heathrow during December 1962 with similar frequencies for December 1952 when there was an outstandingly persistent fog. Table VI gives the number of hours of dense and thick fog at Kingsway and Heathrow in the Decembers of 1952 and 1962. Comparison of the two Decembers shows that at Heathrow there is a decrease of about 11 per cent in the frequency of thick fog, but an increase of about 20 per cent in the frequency of dense fog, while at Kingsway there is a decrease of about 22 per cent in the frequency of thick fog and a marked decrease of about 57 per cent in the frequency of dense fog.

TABLE VI—NUMBER OF HOURS OF DENSE AND THICK FOG AT KINGSWAY AND HEATHROW IN DECEMBER 1952 AND DECEMBER 1962

	Kingsway		Heathrow	
	Dense fog	Thick fog	Dense fog	Thick fog
	number of hours		*number of hours*	
December 1952	69	81	61	113
December 1962	30	63	73	101

Conclusions.—During the period 1947–62, dense and thick fog occurred more frequently in the suburbs than in central London, except that there was a marked tendency for Kingsway to have more dense fog than Croydon during the first 6 years of the period. The frequency of both dense and thick fog tended to decrease during the 12 years 1947–58, but there was a gradual increase in the frequency at Croydon during this period. Smoke control may have contributed to the marked decrease in the frequency of dense fog at Kingsway for the period 1955–62.

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MARKOV CHAIN MODEL OF COLD SPELLS AT LONDON

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Introduction.—Because of the growing body of evidence that persistence found in many time series of meteorological data is well represented by a Markov chain, it is of interest to apply the model to some of the data in the interesting article by Lowndes[1] on cold spells at London. The model has previously provided useful representations of daily rainfall distributions for a wide variety of geographical and climatic situations (see Gabriel and Neumann,[2] Caskey,[3] and Weiss[4]). Persistence in a time series of wind directions also has been found by Barton, David, and Fix[5] to have characteristics of a multiple-state Markov chain.

The probability of a cold spell continuing.—In the Markov chain model, the probability of any day being a 'cold day' (defined by Lowndes' criteria) depends on whether or not the preceding day was a cold day. The probability is independent of earlier days. Thus, the probability of a cold spell of length n days continuing k further days is p^k, where p is the conditional probability that a day will be cold if the previous day was cold. Note that p is independent of n; that is, p is a constant.

To be in agreement with this Markov chain probability relation, the probabilities for 'further day,' 'further 2 days,' 'further 3 days,' and 'further 4 days' in Lowndes' Table I should be equal to p, p^2, p^3, and p^4 respectively, where p is a constant. Most of the values in his Table II(b), for the summer months, are indeed in excellent agreement with the relation p^k; to good approximation, the probability for cold spells of various lengths continuing for a further day is constant, $p = 0.80$; moreover, the probabilities for 2, 3, and 4 further days are well approximated by $(0.80)^2 = 0.64$, $(0.80)^3 = 0.51$, and $(0.80)^4 = 0.41$ respectively.

The agreement of the probabilities in Lowndes' Table II(a), for the winter months, with the relation p^k is less satisfactory. However, for cold spells of length 6 days or more, the probability of continuing a further day is approximately constant, $p = 0.85$; with this value of p, the values of p^k for $k = 2, 3, 4$ are 0.72, 0.62, and 0.52, again in good agreement with Lowndes' values for 'further 2 days,' 'further 3 days,' and 'further 4 days' respectively. Although the Markov chain property does not hold as well for data in Table II (a) as for data in Table II (b), frequency distributions for the winter months may nevertheless be reasonably well represented by a Markov chain model by using an average value of p, approximately 0.84.

The values of p used in the following section are, in agreement with the above discussion, 0.84 for winter months, 0.80 for summer months, and 0.82 for the whole year.

Frequency of cold spells of four days or more.—In the Markov chain model, the frequency f_n of cold spells of length n days ($n \geqslant 4$) is given by the following formula which is obtained by simple algebraic manipulation of equations in earlier papers:[2,3]

$$f_n = N(1 - p)\, p^{n-4},\ n \geqslant 4,$$

where N is the total number of cold spells of length 4 days or more, and p is the conditional probability discussed in the preceding section. From Lowndes' Figure 2[1] the values of N are 162 for winter, 194 for summer, and 356 for the whole year. The respective values of p are 0.84, 0.80, and 0.82, as selected in the preceding section.

With these values of N and p, the above formula was used to compute values of f_n which may be compared with those given by Lowndes' Figure 2. The comparison is made in our Table I. The agreement of Lowndes' frequencies with the computed frequencies appears to be sufficiently close, especially for cold spells 5 days or more in length, to justify using the Markov chain model as a simple representation of the frequency distribution of cold spells at London. The departure of the model frequency from the observed frequency of spells of 4 days in winter (also reflected in the whole year comparison) is not surprising in view of the correspondingly large departure of the first entry in Lowndes' Table II (*a*) from the average value of all entries on the first row.

TABLE I—COMPARISON OF OBSERVED FREQUENCY (LOWNDES' FIGURE 2) WITH COMPUTED MARKOV CHAIN FREQUENCY OF EACH LENGTH OF COLD SPELL

Length of cold spell in days	Winter months		Summer months		Whole year	
	Observed	Computed	Observed	Computed	Observed	Computed
4	38	26	39	39	77	64
5	24	22	26	31	50	53
6	15	18	27	25	42	43
7	14	15	23	20	37	35
8	10	13	17	16	27	29
9	8	11	11	13	19	24
10	9	9	11	10	20	19
11	5	8	6	8	11	16
12	4	6	6	7	10	13
13	6	5	7	5	13	11
14	2	5	5	4	7	9
15	5	4	1	3	6	7
16	1	3	4	3	5	6
17	3	3	0	2	3	5
18	5	2	0	2	5	4
19	1	2	3	1	4	3
20	3	2	1	1	4	3
21	2	1	3	1	5	2
22	0	1	1	1	1	2
23	0	1	2	1	2	1
24	0	1	0	0	0	1
$\geqslant 25$	7	4	1	1	8	6
Total	162	162	194	194	356	356

Conclusion.—The data on cold spells at London, given in Figure 2 and Table II of Lowndes' paper, may be approximated by a Markov chain model. The data for the summer months are particularly well fitted by a Markov chain in which the conditional probability p of a day being cold, if the preceding day was cold, is 0.80. The data for the winter months and for the whole year, excluding cold spells of length 4 days, are also well represented by a Markov chain in which p is 0.84 and 0.82, respectively.

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SUBSIDENCE IN THE MIDDLE AND LOWER TROPOSPHERE—PART I

By C. J. BOYDEN

Summary.—A criterion for subsided air is adopted in terms of the dew-point depression at the 700 mb or 500 mb level. The existence and slope of a column of subsided air are related to sea-level pressure, the speed and vertical shear of wind, and the vertical gradient of potential wet-bulb temperature. The results are consistent with subsided air originating mainly in descent down the transition zone of a frontal surface, the dryness subsequently extending in depth by further subsidence.

[Part II of the paper examines more closely the history of subsided air from the time it descends a frontal transition zone until it settles in an area of high pressure. From a comparison between computed downward velocity and dryness it is seen that subsided air quickly moves away from its source. The lower boundary of the frontal mixing zone in air joining an anticyclonic circulation is identified with the anticyclonic inversion. Dry air over an anticyclone is found to exist primarily through advection, though subsidence within the circulation makes the greater contribution if the anticyclone becomes highly developed.]

Introduction.—Subsidence at any level is determined by the divergence in the underlying layers of atmosphere. It therefore takes place in regions which tend to retain their position relative to features of the flow pattern. However, since at most levels the wind speed is greater than the speed of the isobaric features, any subsided air is likely to be carried away from the part of the upper pattern where the subsidence took place. Only in a closed, slow-moving circulation, such as a persistent anticyclone, is subsided air able to remain subjected to subsidence.

This paper is concerned with the manner in which regions of subsidence and areas of subsided air (particularly at the 700 mb level) are related to the pattern of upper winds and more especially to the sea-level analysis. Subsidence is prominently associated with the frontal surface, where ascending air often has its counterpart in an underlying layer of descending air (see, for example, Sawyer[1]). There is also broad-scale subsidence over the anticyclone, particularly during the period of growth. These are two manifestations of subsidence which differ in character. Frontal subsidence takes place in a layer of air of much the same depth as a frontal transition zone, but it is accompanied by horizontal motion greatly exceeding the vertical descent, at least in the lower half of the troposphere; frontal subsidence at the 700 mb level extends over an area comparable in size with that covered by the frontal rain. Subsidence over an anticyclone, on the other hand, is more gradual than frontal subsidence and takes place more nearly in the vertical.

It will be shown that a substantial part of the subsided air in the lower troposphere originates at a frontal surface. In due course much of this air settles over developing anticyclones because these are systems over which the

wind speed decreases. Further subsidence takes place over the growing anticyclone because of broad-scale divergence, including frictional outflow, but only over the strong and persistent anticyclone is this component of the subsidence as large as the frontal subsidence to which the air was subjected before it joined the anticyclonic circulation. Accordingly, the term 'anticyclonic subsidence' will be applied only to the subsidence undergone by anticyclonic air after its surface circulation becomes closed.

In more detail the ideas which will be developed are as follows. Subsidence takes place down the transition zone of most warm fronts in the middle troposphere and mainly at this type of front. The subsided air normally found behind a cold front mostly arrives in that state from the upwind ridge and warm front. Subsided air over a ridge or cold anticyclone is located just below its bounding frontal surface, some further subsidence taking place through a great depth during and after the growth of the anticyclone. The transition from subsided air in a frontal zone to subsided air in a cold anticyclone is claimed to be one in which the lower boundary of the frontal transition zone becomes the inversion of the anticyclone. During this process there is a sinking towards the horizontal of the frontal and isothermal surfaces, and eventually turbulence in the lowest layers of the atmosphere exerts a controlling influence on the structure of the inversion.

This sequence of events was studied in relation to fronts and anticyclones existing in the winter months. The anticyclones were of cold origin and were not systems of great maturity. No attempt was made to follow the evolution of well established or semi-permanent anticyclones since it would have been difficult to determine the source of the air and moreover adiabatic assumptions would not have applied.

The measurement of subsidence.—Direct measurements of subsidence usually depend on the assumption that the air has a property which can be regarded as conservative for as long as the subsidence is taking place. It will be shown that subsidence can normally be regarded as a fairly rapid process up to the time the air becomes stagnant over a persistent high. Until this stage is reached it therefore seems justifiable to regard upper air temperature changes as adiabatic. There are then three main methods by which the air can be followed during subsidence. Each has certain advantages and disadvantages.

The conservation of potential dry-bulb temperature (θ) is commonly used because this element is measurable at high levels where a humidity measurement is no longer reliable enough to be used as a tracer. A drawback to θ is that it takes no account of the latent heat of cloud and therefore assumes the atmosphere to be cloudless. When subsidence is being measured this may not be important. There is, however, a further limitation. All that can be measured by a local change of θ is the component of motion perpendicular to isentropic surfaces. When subsidence takes place nearly along these surfaces, as frontal subsidence does, there is little indication in the change of the isentropic field.

The potential wet-bulb temperature (θ_w) is a refinement of θ in that it takes into account the latent heat of evaporation and condensation. This advantage is one which counts for more when ascent of air is being studied than when the problem is concerned with descent. The important feature of θ_w, unlike θ, is that it persists during vertical motion as an identification of an air mass. But

there are two drawbacks to the use of θ_w which are not possessed by θ. Firstly, it is less sensitive than θ in measuring vertical movement because in the average atmosphere its vertical gradient is smaller. Secondly, θ_w requires a knowledge of humidity, an element difficult to measure accurately and one which cannot at present be estimated satisfactorily from radiosonde observations above mid-troposphere.

In the present investigation considerable use has been made of a quantity not far removed from relative humidity, namely the depression (Δ) of the dew-point below the dry-bulb temperature. Its great advantage over θ and θ_w is that it provides a measure of descent in the vertical, since isobaric surfaces are practically horizontal, and it is proportional to the height through which the air has descended from a state of saturation, regardless of the height or temperature at which the subsidence takes place. Since in cloudless air Δ increases by nearly 1°C for each 100 m descent, it is a very sensitive measure of subsidence. As with θ_w, its use is confined to the middle and lower troposphere and its precision is limited by the accuracy of humidity measurements. It is therefore desirable to consider how effectively Δ can be used in the present investigation.

The use of humidity measurements up to the 500 mb level.—In the British radiosonde the humidity element is a strip of goldbeater's skin, which measures the relative humidity. It suffers from the disadvantages of hysteresis and lag. The magnitude of both effects has been studied by Glückauf.[2]

Glückauf concluded that hysteresis was small at relative humidities exceeding 70 per cent. As an example of the effect in air drier than this he found that, if the instrument read correctly a relative humidity of 10 per cent, its reading was about 8 per cent too low when the humidity was increased to 40–50 per cent. Hysteresis appeared to be independent of temperature in the range that is found below mid-troposphere over southern England in winter.

It is not easy to relate Glückauf's figures for lag to the readings obtained from a radiosonde. At medium humidities the time for half the magnitude of a sudden change of relative humidity to be recorded varied from 6 sec at 0°C to 18 sec at −11°C (corresponding to a height rather above the 700 mb level in winter) and 42 sec at −27°C (roughly the temperature at the 500 mb level). A somewhat greater lag was found when the relative humidity was very low. In terms of ascent by a British radiosonde, 10 sec corresponds to a rise of about 60 m.

As a partial safeguard against the use of unreliable humidities, the British practice is not to report a dew-point in certain circumstances. It is omitted on all occasions when the dry-bulb temperature is below −40°C. At temperatures between −21°C and −40°C the dew-point is not reported for relative humidities lower than 10 to 35 per cent (depending on the temperature). At temperatures of −20°C or higher the dew-point corresponding to 5 per cent is reported whenever the relative humidity is observed as 5 per cent or less. As a result of this procedure it was found that in the layer from 700 mb to 500 mb about 3 per cent of the dew-points in three winter months were indeterminate, though of course an upper limit for the dew-point was known on every occasion.

On the upper air ascents it was usually found that extremely dry air was concentrated in a shallow layer. On the majority of occasions it was therefore considered that over-estimation of the lowest dew-points, either because of the lag or because the dew-points were indeterminate under the reporting procedure, applied over too small a depth to have any material effect on the conclusions reached.

To a large extent the analysis has avoided the complications described above by regarding air as subsided when the dew-point depression was 20°C or more, without normally attempting to discriminate further. It should also be mentioned that in an analysis based largely on humidities at the two standard levels of 700 mb and 500 mb it is not profitable to seek great precision. The driest air is to be found at a variety of heights, and at the 700 mb level in particular the humidity may vary considerably with time simply because of small vertical movements of a layer in which the vertical gradient of humidity is large. In spite of this reservation it was found that when there was subsided air at 700 mb this was on the average the level of the driest air in the lower half of the troposphere. Thus if a single level is used for detecting subsidence in the lower troposphere, 700 mb is probably the best.

Comparative subsidence at the levels of 700 mb and 500 mb.—An analysis was made of radiosonde observations taken twice daily over the British Isles during January, November and December 1962. These months were chosen because there was a variety of weather over the British Isles and an absence of prolonged anticyclonic periods.

Table I shows the frequency of dew-point depressions(Δ) observed at all radiosonde stations in the British Isles. Figures in brackets give the number of indeterminate values included in the adjoining total. Almost all of these occurred when the dew-point depression at 500 mb exceeded 21°C and at 700 mb exceeded 30°C, and it was largely for this reason that $\Delta \geqslant 20$°C was chosen as the criterion for subsided air.

TABLE I—FREQUENCIES OF DEW-POINT DEPRESSION IN RANGES OF 5°C OVER THE BRITISH ISLES IN JANUARY, NOVEMBER AND DECEMBER 1962

Level	Dew-point depression (°C)							
	0–4	5–9	10–14	15–19	20–24	25–29	30–34	35–39
	number of occasions							
500 mb	332	579	347(1)	187(4)	144(40)	21	30(21)	0
700 mb	456	462	285	177	133	61	57(35)	6

Note: When the depression was 20°C or more the air was regarded as subsided. Figures in brackets give the number of indeterminate values included in the adjoining total.

Bearing in mind that indeterminate dew-points usually relate to a very narrow tongue within the subsided air, it is reasonable to regard them as of little significance in assessing the depth through which the air has subsided. (This was confirmed by a separate analysis of the Crawley figures, in which there were few indeterminate values.) It is then found that, on the average, subsided air (as defined) descended from a state of saturation through about 2½ km to both the 500 and 700 mb levels. This is equivalent to a little more than 150 mb down to the 500 mb level and about 200 mb to the 700 mb level.

Subsidence from 300 mb down to the 500 mb level, or from 400 mb to 700 mb, appears to be very rare. Moreover, all these figures should be regarded as over-estimating the average subsidence during a single development, since it is unlikely there would have been complete saturation when the subsidence began. Subsidence involving cloudy air would not of course be allowed for in Table I since the dew-point depression does not respond to the vertical motion of cloudy air.

The association between subsided air at the 700 mb and 500 mb levels.—Table I shows that for the British Isles as a whole, subsided air at 700 mb was shown on one report in six, and subsided air at 500 mb on one report in eight. These proportions apply only to the period examined and not to a single station. The question that next arises is whether subsidence is to be expected at both levels at the same time and if so whether one mass of subsided air is likely to lie vertically above the other.

To ascertain this an analysis was made of the reports from Aughton (Liverpool), this station being chosen because it is near the middle of the upper air network. In the three months there were 34 reports of subsided air at 700 mb over Aughton, and on 18 of these occasions it was also subsided there at the 500 mb level. Of the remaining 16 occasions there was subsided air at 500 mb over some part of the British Isles on all but 2.

Subsided air at 500 mb existed over Aughton on 30 occasions, 18 being those when the air at 700 mb also was subsided. Of the remaining 12 occasions there was subsided air at 700 mb over some other stations on all but 3.

Thus on 92 per cent of the occasions when there was subsided air over Aughton at either level there was subsided air over some part of the British Isles at the other level. (The 92 per cent may be contrasted with the chance probability of 51 per cent.) This 92 per cent comprises 52 per cent when there was subsided air at both levels over Aughton (and probably elsewhere) and 40 per cent when subsidence at the second level occurred elsewhere than over Aughton. The figure would certainly have been higher than 92 per cent but for the occasions when subsided air at one level escaped the observational network.

These results lead to the expected conclusion that subsidence takes place at much the same time at both levels, and since, as shown earlier, the descent is through the same average depth to both the 700 mb and 500 mb levels, it is reasonable to regard subsidence in the middle and lower troposphere as a single mechanism.

The figures also show that on nearly half the occasions of subsided air at 700 mb there was a slope to the tongue of subsided air. There are two causes of the slope and they are of equal importance. The first is that most subsidence takes place down the transition zone of a frontal surface. The second is that within the transition zone, between the 700 mb and 500 mb levels, there is a shear of wind in the direction of the surface front. Thus a tongue of air which subsides down a frontal surface subsequently tends to become aligned along the direction of the front. A cross-section perpendicular to a front therefore cuts through the tongue of subsided air, and if dry air is found at, say, the 700 mb level, the isopleths of dew-point depression are likely to be closed around it rather than to include the air at 500 mb (see, for example, Figure 2).

When such a tongue of subsided air enters an anticyclonic circulation it moves differently at different heights and the relationship between subsided air at the two levels becomes obscured. Nevertheless when subsided air at the 500 mb level over a well developed anticyclone is found vertically above subsided air at 700 mb its existence is usually due to anticyclonic subsidence acting both on the subsided air in the frontal transition zone and on the air above it.

Potential wet-bulb temperature as evidence that subsidence is essentially a frontal development.—A frontal boundary is defined in terms of a temperature gradient. The concentration of isothermal surfaces in the region of a front may be changed in position or strength by differential subsidence and there is then some doubt as to precisely where the frontal surface lies. The potential wet-bulb temperature (θ_w) is not altered by subsidence and is therefore an excellent parameter for maintaining historical consistency.

Figure 1 shows the distribution of $\delta\theta_w$, the difference in potential wet-bulb temperature between 500 mb and 700 mb, taken from the Crawley radiosonde ascents during the 6 months January 1961 and 1962, November 1961 and 1962 and December 1960 and 1962. The histogram shows frequencies for all occasions and separately for those when the air at 700 mb was subsided. All occasions taken together gave a mean $\delta\theta_w$ of 3.1°C (median 2.5°C). This mean was based on frontal as well as non-frontal situations and for this reason alone is much higher than the 1–1.5°C which Belasco[3] found for various air masses in winter.

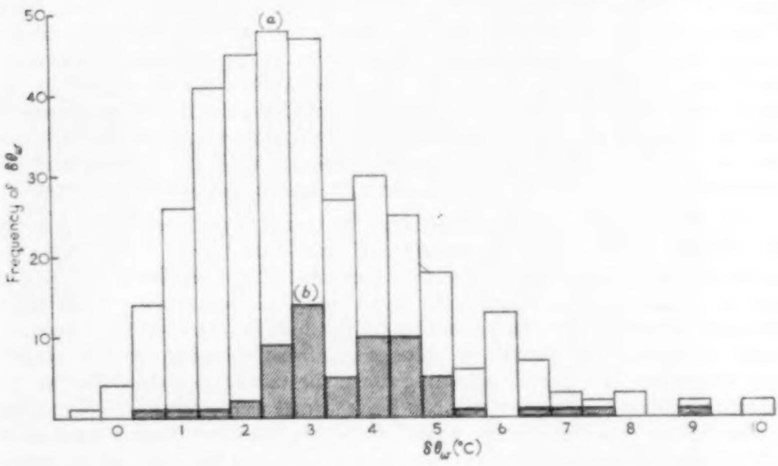


FIGURE 1—FREQUENCY DISTRIBUTION OF POTENTIAL WET-BULB TEMPERATURE DIFFERENCE ($\delta\theta_w$) BETWEEN THE 500 MB AND 700 MB LEVELS DURING SIX WINTER MONTHS

(*a*) On all occasions and (*b*) on occasions when the air at 700 mb was subsided.

Taking only those occasions when the air was subsided at 700 mb (and perhaps also at 500 mb) the mean $\delta\theta_w$ was found to be 3.7°C (median 3.4°C). Being

significantly higher than average this figure supports the thesis that when the air at 700 mb was subsided the air between 700 mb and 500 mb originated in a frontal zone. A feature of particular interest is that 84 per cent of the values of $\delta\theta_w$ for subsided air lay between 2.5°C and 5.0°C, between which values there were 54 per cent of all observations. Within this range there was a 27 per cent probability that the air was subsided, as against 6 per cent outside it. Similar analyses on occasions when air was subsided at both levels gave much the same results.

A downward gradient of potential wet-bulb temperature somewhat greater than average is therefore likely to be found in subsided air, and it is almost a requirement that $\delta\theta_w$ should reach at least 2.5°C.

In reaching this conclusion it is necessary to confirm that the larger values of $\delta\theta_w$ did not occur because the selection of subsided air at 700 mb involved the selection of air with low θ_w at that level. This proved not to be so since the mean θ_w in subsided air at 700 mb was 7.4°C, as against 6.9°C for all occasions, whether subsided or not.

Another possibility to be considered is whether the high mean $\delta\theta_w$ in subsided air could have been a consequence of the subsidence rather than a prerequisite. It is thought that this was not so because the same mean $\delta\theta_w$ was found whether the air was subsided only at 700 mb or at both levels, and because $\delta\theta_w$ depended little on the degree of subsidence of the air.

Subsidence at a warm-front surface.—Figure 2 depicts a cross-section ahead of a fairly typical warm front, based on the soundings from Camborne, Crawley and Hemsby at 0000 GMT on 20 December 1962. The frontal transition zone is shown by the concentration of isopleths of potential wet-bulb temperature and, as usual, the most highly subsided air is centrally placed in this band; the lower edge of the dry air zone is marked as a surface of subsidence. It will be observed that the isopleths of dew-point depression are closed below the 500 mb level, the subsided air aloft having been carried forward of the subsided air at 700 mb by the wind shear along the direction of the front.

This paper makes no attempt to discuss the causes of subsidence but it might be doubted whether the average pattern of divergence is such as to require the same amount of subsidence to both the 700 mb and 500 mb levels and yet be such as to halt the descent abruptly only a small way below the 700 mb level. However, it is not easy to establish whether the descent ceases where Δ becomes small or whether Δ is small, in spite of adiabatic warming, because frontal rain evaporates into the air subsiding down the transition zone. Whether the subsidence ceases or not the rain can be regarded as introducing a boundary to the dry air, and the average width of a warm-front rainband is such as to prevent dry air from appearing below the level of about 800 mb. Dry air might exist at lower levels in the transition zone if the rain belt were narrow or of negligible intensity, but then it is likely that the front would be thermally weak and the high-level wind shear required for subsidence would be absent. Since most dry inversions above the ground, whether directly associated with fronts or occurring in non-permanent anticyclones, are regarded as being of frontal origin, the comparative uniformity of the level at which they first appear is considered to be due to the uniform width of the band of frontal rain and the uniformity of frontal slope.

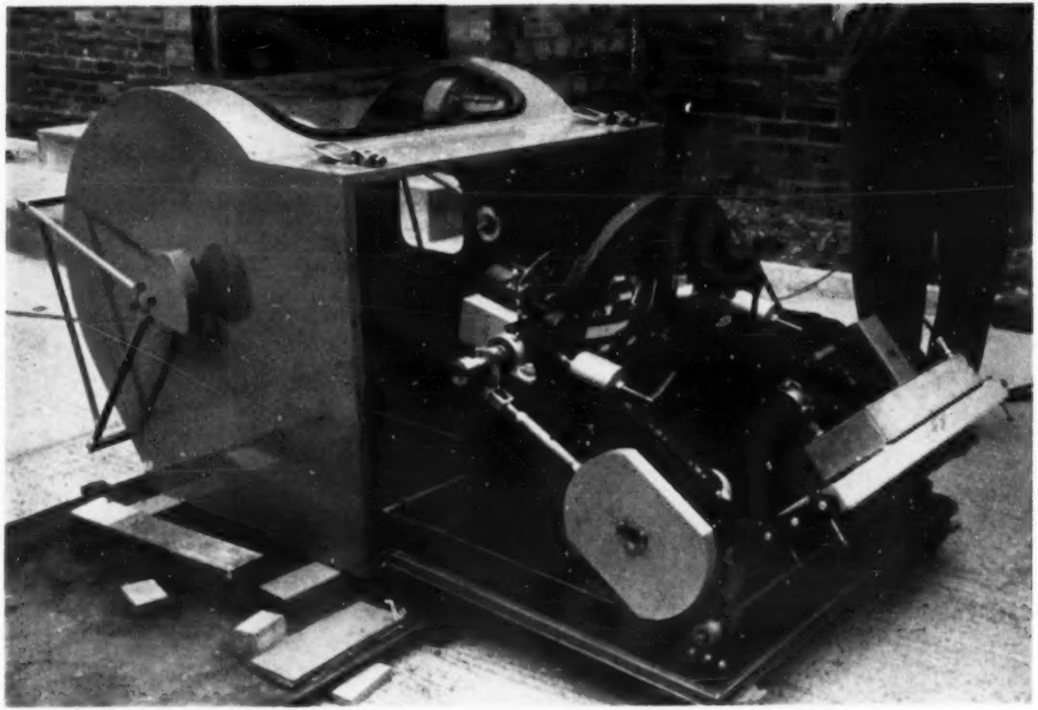


PLATE I—THE TRANSMITTER OF THE CLOUD BASE RECORDER

The main chassis is shown run out on tracks into the servicing position (see page 154).

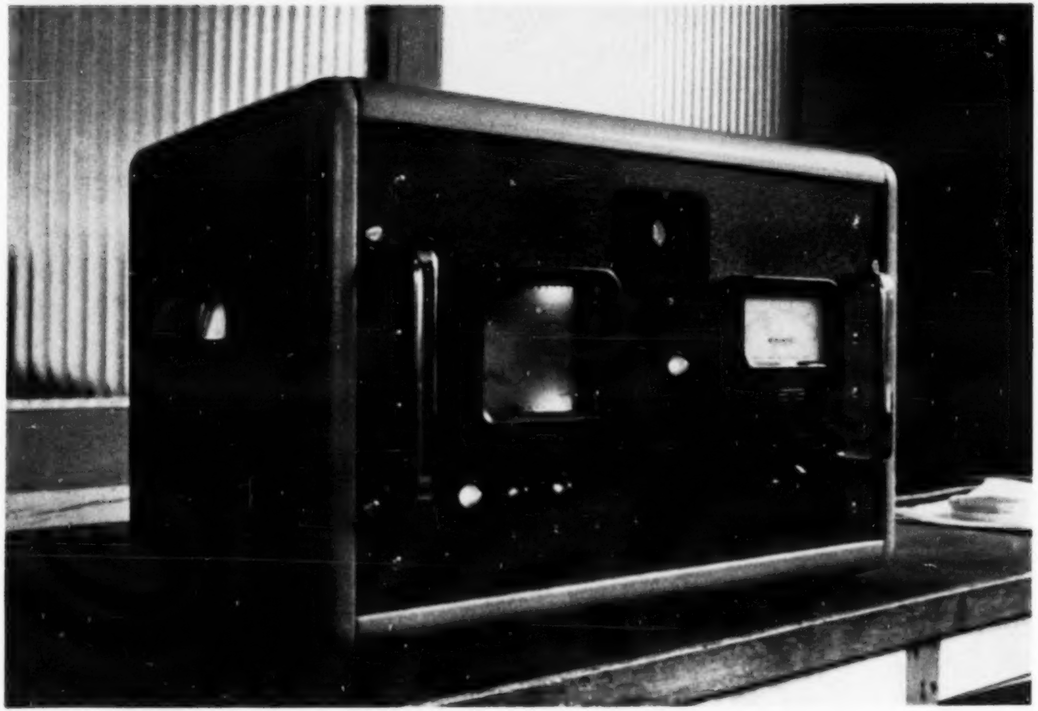
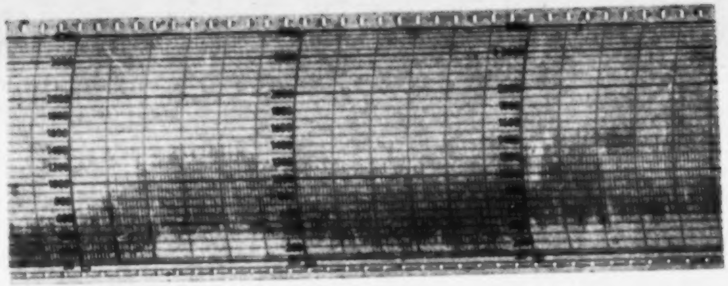
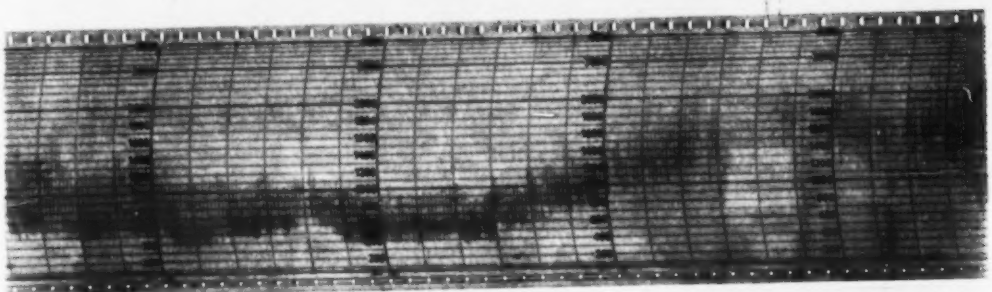


PLATE II—THE RECORDING UNIT OF THE CLOUD BASE RECORDER

See page 154.



Fog lifting into low stratus.



Stratus lifting and dispersing.

PLATE III—CHARTS FROM THE CLOUD BASE RECORDER

See page 154.

To face p.145

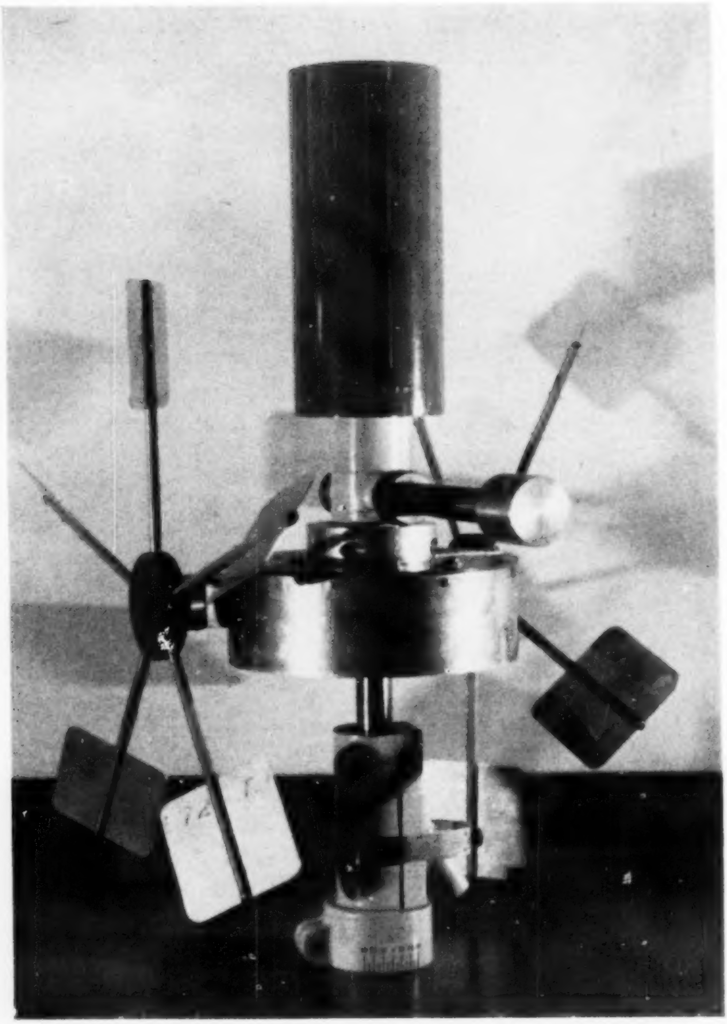


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PLATE IV—WIND DIRECTION HEAD FOR THE AUTOMATIC WEATHER STATION

This contains 18 switches to select voltages equivalent to 20° steps (see page 155).

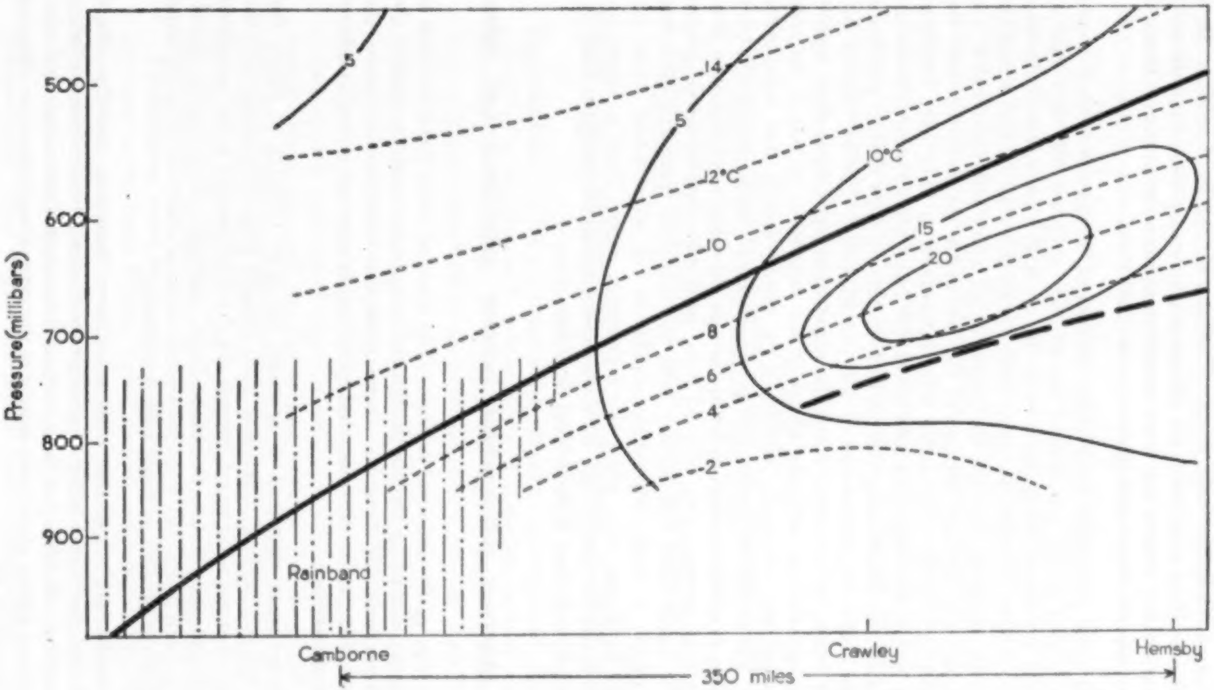

FIGURE 2—CROSS-SECTION THROUGH A WARM-FRONT SURFACE AT 0000 GMT ON 20 DECEMBER 1962

——— Isopleths of dew-point depression (Δ).

- - - Isopleths of potential wet-bulb temperature (θ_w).

——— Frontal surface, — — — surface of subsidence.

Subsidence at a cold-front surface.—Essentially a section through a cold-front surface is similar to one through a warm-front surface. A difference which is often found is the extension of the dry air near the 700 mb level to a point ahead of the surface cold front, in which case the front tends to be a fairly weak one. If, as is believed, the dry air originates far away from the cold front, this overhang beyond the front would result from the low-level thermal wind being appreciably veered relative to the cold front.

Whereas some subsidence takes place because of divergence behind a cold front, the history of the post-frontal air strongly supports the view that in the main the subsidence takes place when the air is at a considerable distance from the cold front. Trajectories were drawn of subsided air behind a number of cold fronts, assuming that the air moved at all times with the wind at 700 mb. The task was difficult because of the inevitable uncertainties over the Atlantic but satisfactory trajectories were considered to have been obtained for the air at 700 mb behind 10 cold fronts. Of these, one showed that the air travelled with the fast-moving surface low for the 1½ days during which the system was within the boundaries of the 700 mb chart. The air behind two other cold fronts, on occasions when the trajectories were more than usually uncertain, appeared to originate ahead of the depression to which the cold front belonged and eventually arrived in the north-westerly flow behind the cold front. The remaining seven centres of subsided air could be tracked back on the charts available at least as far as the upwind ridge or anticyclone. This journey took an average time of 2–2½ days, so if the subsided air originated ahead of a warm front still further west the complete travelling time was probably nearly a week, depending mainly on the wind speed across the ridge. It is significant that when the trajectories passed close to upper air stations there were reports of dry air on sufficient occasions to suggest that the air was usually subsided at some level the whole time.

Some observed relationships between subsidence and other features.—

(i) *The slope of the isothermal surfaces.*—The thermal wind speed through a layer is proportional to the vertical gradient of temperature and the slope of the isothermal surfaces. Of these two components the latter usually shows the greater variability, so the thermal wind speed can be taken as a rough measure of the isothermal slope.

The frequency of occasions of subsided air over Crawley at either the 700 mb or the 500 mb level, but not at both, showed little relationship with the 700–500 mb thermal wind speed, though the driest air tended to be associated with the lowest speeds. On the other hand, subsided air occurring simultaneously at both levels over Crawley existed twice as often with thermal wind speeds below the median as when they exceeded it.

These results are consistent with subsidence occurring initially where isothermal surfaces have a fairly large slope; with continued subsidence being accompanied by a flattening of these surfaces towards the horizontal; and with later subsidence taking place more nearly in the vertical and therefore affecting a deeper column of air.

(ii) *Wind speed at 700 mb.*—The median speed at 700 mb over Crawley in the 6 months was 23 knots, yet 10 of the 63 observations of subsided air coincided with winds of 40 knots or more, the highest being 79 knots. With speeds above the median, subsided air was only 32 per cent less likely than with speeds below it. Similar figures were found for subsided air at the 500 mb level. These results are consistent with subsidence occurring mainly in stronger winds, the air remaining subsided when it enters a region of lighter winds.

(iii) *Sea-level pressure.*—Subsided air was found on a few occasions with sea-level pressures even below 1000 mb. With surface pressures of 1030 mb or more the air was subsided on 46 per cent of occasions at 700 mb and 26 per cent at 500 mb. Subsidence at only one level occurred about twice as often when pressure was above the median as when it was below it, but nearly 90 per cent of the observations of subsided air extending to both levels occurred with surface pressures in the anticyclonic half. Thus, whereas subsided air in a shallow layer is associated more with high than with low surface pressure, the major characteristic of high-pressure systems is that the subsided air extends through a considerable depth.

Note.—Part II will be published in June 1964.

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551.509.314:551.509.323

THE FORECASTING OF HIGH TEMPERATURES AT REDCAR

By D. C. HENDERSON

Introduction.—This short note has been prepared to indicate that a successful method of forecasting high temperatures at a specific location can be devised using simple techniques. It is suggested that a similar technique, perhaps using different parameters, could be employed for this type of problem at other locations.

The problem.—In hot weather bacteria tend to multiply and it is possible for them to affect imitation cream. A firm of bakers near Middlesbrough wished to receive warnings of high temperatures from Manchester Weather Centre so that they could cease manufacture and distribution of cakes containing this cream and so obviate any possible risk to public health. The client agreed that it was preferable for warnings to be issued which subsequently prove false rather than have high temperatures without receiving a warning. It was decided that the forecasting technique should as far as practicable use prebaratics and pre-thickness charts of the Central Forecasting Office.

Techniques used to devise a forecasting method.—Observations for 1200 GMT in the *Daily Weather Report** and for 0001 GMT in the *Daily Aerological Record** were examined for each occasion from 1956 to 1962 when the temperature at Redcar (the nearest reporting station) reached 75°F. Brief details of the surface and upper air situations were extracted for each occasion.

*Meteorological Office. *Daily Weather Report*: *Daily Aerological Record*. London, HMSO 1956–1962.

(i) It was found that in the 40 cases examined:

(*a*) An anticyclone existed in the area 55N 01E–55N 19E–49N 19E–49N 01E–55N 01E on 29 occasions.

(*b*) The geostrophic wind was from between 200° and 250° on 27 occasions.

(*c*) The pressure at mean sea level was above 1015 mb on 33 occasions.

(*d*) There was a warm ridge on the 1000–500 mb thickness chart between 10°W and 10°E on 35 occasions.

(*e*) In the months of July, August and September (28 occasions) the 1000–500 mb thickness was 5600 metres or more on 22 occasions. In June and October (11 occasions) it was 5560 metres or more on 8 occasions.

(ii) On 37 occasions there were 3 or more of the above parameters present when the temperature reached 75°F.

(iii) The presence or absence of these parameters was examined on all days (June to September) for the years 1960–61. On 12 days three or more parameters were present with the temperature reaching 75°F. On 18 days three or more were present with the temperature below 75°F. On no occasion did the temperature reach 75°F with less than three present.

(iv) In an attempt to reduce the number of wrong forecasts the following additional parameters were examined:

(*a*) *Geostrophic wind speed.*—It was thought strong winds would keep the temperature down but this was found to be incorrect. It was also found that with light winds a sea breeze often developed and the temperature remained below 75°F.

(*b*) *Direction of wind.*—It was found that between 1956 and 1962 the temperature never reached 75°F when the geostrophic wind was from between 340 and 160 degrees, that is, from a seaward direction at Redcar.

(*c*) *Sunshine.*—It was found that in the same years there had to be at least 3 hours sunshine for the temperature to reach 75°F. The possibility of using other values of sunshine hours as an additional parameter was examined but was found to be unsuitable.

Conclusion.—Warnings are now issued on the following basis:

The 1200 GMT prebaratic and 0001 GMT pre-thickness charts are examined to see if at least 3 of the parameters mentioned in (i) above will be present. If so, a warning is issued unless (*a*) the geostrophic wind direction is from between 340° and 160° through 090° or (*b*) little or no sunshine is expected the next day.

Temperatures from Redcar are not received at the Manchester Weather Centre daily but a check has been made using data supplied by Headquarters. On this basis, of the 40 days with high temperatures which occurred between 1956 and 1962, 37 would have been forecast. In 1960 and 1961 22 warnings would have been issued, 12 correctly, 10 incorrectly and on no occasion would a warning have been missed. In 1963 3 parameters (with the restrictions absent) occurred on 6 occasions. The temperature reached at least 75°F on 3 of these occasions. There was 1 occasion when the temperature reached 77°F with only 2 parameters being present.

Acknowledgement.—The author would like to acknowledge the assistance given by the Climatological Services Branch of the Meteorological Office in supplying the maximum temperatures for Redcar, and the helpful advice given by the Techniques and Training Branch.

551.521.11:551.589.5:519.272

RELATION BETWEEN MEAN DAILY MAXIMUM TEMPERATURE AND MEAN DAILY SUNSHINE DURATION: VARIATIONS ACCORDING TO TIME OF YEAR AND WIND DIRECTION, DURHAM OBSERVATORY, JULY 1937 TO JUNE 1962

By A. J. W. CATCHPOLE, B.Sc.,
(Birkbeck College, London)

Summary.—Daily observations of maximum temperature and sunshine duration were reduced to means calculated according to time of year and wind direction. A high degree of positive correlation was observed between the temperature and sunshine means. Clearly this arose from the similarity between the seasonal régimes of both groups of data. When these seasonal changes were eliminated the positive correlations were of smaller magnitude and were often insignificant. This reduction in the degree of correlation was partly due to the small total variations in mean maximum temperature and mean sunshine duration according to wind direction in some months. In winter, when the relatively large contrast between continental and maritime influences emphasized these variations, the positive correlations were again of higher magnitude. Diagrams are given showing the variations of temperature and of sunshine with wind direction.

Introduction.—The results contained in this analysis emerged during a study of the general variations of maximum temperature and sunshine duration according to wind direction and the procedures adopted for the extraction and examination of the data were those best suited for this general purpose. Sunshine and temperature observations at Durham Observatory are made according to the requirements of a normal climatological station and the data for this study were extracted directly from the record.

The use of wind data is complex and this is especially true in an analysis concerned with mean or total daily conditions rather than spot observations at 0900 hours or 2100 hours. In this case the wind data were extracted from the record of the pressure-tube anemograph since this provides the best estimate of mean daily wind direction. Each anemogram was inspected and classified into one of 17 groups. These groups included 16 wind directions and an additional group for those days which could not be allotted a mean direction either because of calm conditions, frontal wind change, failure of the instrument etc. Eventually it was found that the classification was too detailed and a more coherent pattern was obtained by reducing the direction groups to 8. As a result 'north' includes 'north-north-east,' 'north-east' includes 'east-north-east' etc. in this paper.

This is a subjective technique but it has the advantages of providing a better estimate of total daily conditions than means of observations at particular hours and being much simpler than a graphical or arithmetical analysis of each chart. An average of between 12 per cent and 20 per cent of the total number of days in each month could not be allotted a mean wind direction by this method and were omitted from the analysis. This percentage was higher in summer, and between the two extremes there was a fairly smooth curve. This summer maximum is probably caused by the relatively high frequencies of low wind speeds at that time.

For each day during the 25 years under consideration, a maximum temperature, a sunshine duration and a mean wind direction were extracted from the record. Initially the temperature and sunshine data were classified into two sets of 96 frequency distributions, each distribution referring to a particular month and wind direction. Means were calculated for each of the frequency distributions. The variations of these means according to wind direction have been emphasized in Figure 1 by plotting individual differences from the appropriate monthly means. In this way seasonal changes are ignored and it is seen that the monthly curves of anomaly of mean maximum temperature and mean sunshine duration are occasionally similar in form. This is mainly true in the winter months when wind direction has a particularly marked effect on the magnitude of the various means. In this paper there will be a discussion of the precise nature of the relationships between the monthly curves in Figure 1.

Seasonal variations.—An objective view of the relationships between the two groups of means cannot be obtained until the effects of seasonal régime are eliminated. Any two sets of data which assume higher magnitudes in summer will appear to be correlated although they may be unrelated. In the present case expected degrees of positive correlation are observed when the corresponding means are plotted in climogram form.

Variations according to wind direction.—

(i) *Each month.*—Seasonal changes have been eliminated in Figure 1 and in subsequent calculations by the use of relative, rather than absolute, values. For example in January the mean duration of sunshine is 1.6 hours while the equivalent value calculated for north winds alone is 0.9 hours. Therefore the 'anomaly' with north winds in January is −0.7 hours.

Figure 1 indicates that in particular months, mean maximum temperatures and mean sunshine durations vary considerably according to wind direction. This is especially true in winter when the greatest contrasts between air masses are expected. For example in February the mean maximum temperature with east winds is six standard deviations below the equivalent mean with south-west winds. Differences between the means of this magnitude are observed from December to March with both the temperature and sunshine data. By contrast, differences are low in summer and often they are insignificant. This is relevant because a positive correlation between the two groups of means is more likely to occur in those months with relatively large differences (see Table I).

TABLE I—MONTHLY CORRELATION COEFFICIENTS BETWEEN THE VARIATIONS ACCORDING TO WIND DIRECTION OF MEAN DAILY MAXIMUM TEMPERATURE AND MEAN DAILY SUNSHINE DURATION (8 PAIRS OF MEANS PER MONTH), DURHAM OBSERVATORY, JULY 1937 TO JUNE 1962

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
r	0.95	0.82	0.53	0.11	0.38	0.34	0.54	0.57	0.26	0.38	0.32	0.40
Pe	0.02	0.08	0.17				0.17	0.16				

r = correlation coefficient (all values are positive),
Pe = probable error of correlation coefficient (only calculated where required for significance testing).

Probable error testing indicates that these correlation coefficients are highly significant in January and February, and only moderately significant in March, July and August.

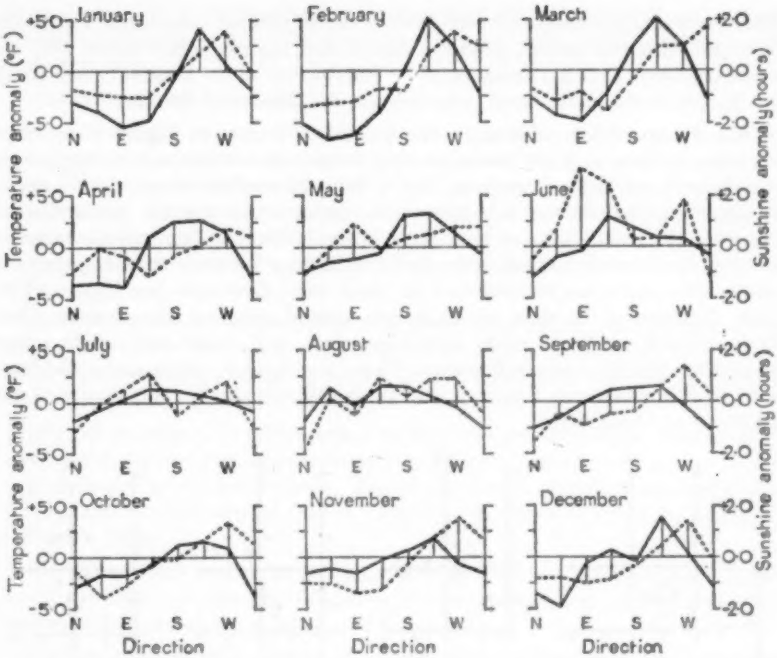

FIGURE 1—VARIATIONS OF THE TEMPERATURE AND SUNSHINE ANOMALIES ACCORDING TO WIND DIRECTION IN EACH MONTH; DURHAM OBSERVATORY, JULY 1937 TO JUNE 1962

——— Temperature anomaly, - - - - sunshine anomaly.

(ii) *Seasonal.*—It will be noted that there are smooth seasonal changes in the forms of the curves in Figure 1. In winter the highest means are observed with south-west and west winds. Between April and August these maxima occur progressively with south and south-east winds and there is a return to the original form in the latter half of the year. Consequently there is a larger total range of means with the eastern group of winds, including those from the north, north-east, east and south-east, than with the corresponding western group. Again it is fair to expect higher positive correlations between those pairs of means observed with winds responsible for the greatest total variations (see Table II).

TABLE II—CORRELATION COEFFICIENTS BETWEEN MONTHLY MEAN DAILY MAXIMUM TEMPERATURE AND MONTHLY MEAN DAILY SUNSHINE DURATION (48 PAIRS OF MEANS PER WIND GROUP): CALCULATED ACCORDING TO WIND DIRECTION; DURHAM OBSERVATORY, JULY 1937 TO JUNE 1962

	Eastern group	Western group	Total
r	+0.53	+0.10	+0.45
Pe	0.07		0.05

Eastern group = north, north-east, east and south-east.
Western group = south, south-west, west and north-west.
r = correlation coefficient.
Pe = probable error.

There is a striking contrast here between the significant correlation coefficient observed with the eastern group of winds and the negligible value with the western group. This is a measure of the importance of the seasonal contrasts in the nature of the continental influences on the climate of Britain.

(iii) *Air-mass effects.*—However the individual curves in Figure 1 are often irregular in form and the corresponding temperature and sunshine curves are occasionally markedly divergent. This is likely to result from accidental causes arising from deficiencies in sample size rather than specific climatological processes. It would appear that these irregularities are sufficiently large to obscure any smooth variations in the relationships between the two groups of means when these are studied for individual wind directions (see Figure 2). In these climograms the data are generally massed together into clusters. Only those clusters observed with south-east, east and north-east winds adopt limited tendencies towards linearity. There are regular variations in the locations of the clusters in Figure 2 and these afford valuable summaries of the nature of air-mass effects.

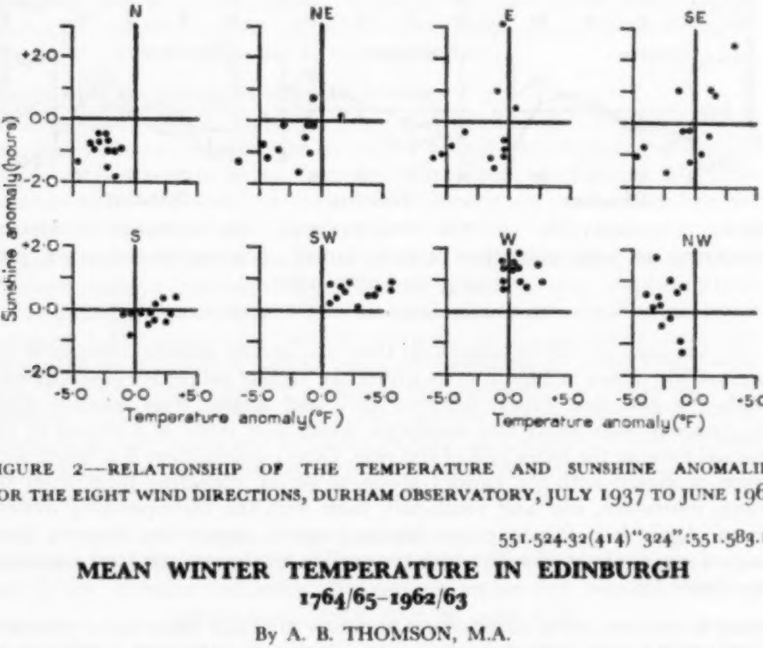

FIGURE 2—RELATIONSHIP OF THE TEMPERATURE AND SUNSHINE ANOMALIES FOR THE EIGHT WIND DIRECTIONS, DURHAM OBSERVATORY, JULY 1937 TO JUNE 1962

551.524.32(414)"324":551.583.14

MEAN WINTER TEMPERATURE IN EDINBURGH 1764/65–1962/63

By A. B. THOMSON, M.A.

Records of temperature made in Edinburgh were used in a statistical examination of mean temperature in the three winter months December, January and February and the winter period (December–February) as a whole. The investigation covered the 199 winters 1764/65–1962/63. The records consisted of the R.C. Mossman series published in World Weather Records 1921–30,[1] combined with data in the Meteorological Office, Edinburgh.

The mean temperature and standard deviation were calculated for each winter month and for the winter as a whole. Each series was then subdivided

at its (mean $\pm \frac{1}{2} \times$ standard deviation) and at (mean $\pm 1\frac{2}{3} \times$ standard deviation) providing five classifications viz. very mild, mild, moderate, cold and very cold.

The main conclusions were:

(i) The winter months showed a general pattern of coldness in the first 100 years and mildness thereafter, but the mild trend was reversed about 1939. There were noteworthy runs when the general pattern of coldness or mildness was the same for consecutive months of the same name, in particular Decembers from 1796 to 1820 (none mild or very mild), Januarys from 1898 to 1939 (none cold or very cold) and Februarys from 1905 to 1928 (only two cold).

(ii) The odds were in favour of persistence of type e.g. cold Januarys were more likely than mild ones after cold Decembers but the character (cold or mild) of a particular month seems to have no connexion with the character of its predecessor of 12 months earlier.

(iii) An examination of the intervals between the 20 coldest months of the same name showed that they were seldom shorter than 3 years, as was also the case with the 20 mildest months. The chances were therefore against a quick recurrence of a January as cold as January 1963 or of a February as mild as February 1961.

(iv) Six winters had mean values below 36°F in the last 100 years against 23 in the first 100 years of the series; the corresponding numbers of winter means of 41°F or above were 13 and 6.

(v) The chances of a cold or of a mild winter following a cold one of the previous year were both about one in four but the figures suggest that a mild winter is more likely to have a mild than a cold successor the next year.

(vi) Of the 20 coldest winters of the series, only two of them (1947 and 1963) occurred in the present century, and these, judged on their mean temperatures, were less severe than some of the earlier ones. The odds were against a quick recurrence (interval less than 3 years) of a winter as severe as any amongst these 20 coldest winters; similarly the odds were against a quick recurrence of a very mild winter.

(vii) The periods 1774–85 and 1809–23 had the greatest concentration (i.e. shortest recurrence intervals) of the 20 coldest winters, and both these periods had also a large concentration of the coldest Januarys.

(viii) There seems no means of judging the future trend but it would be unrealistic to discount the possibility of a recurrence of the low temperature levels of the last half of the 18th and first half of the 19th centuries and, in particular, the striking sequence of low winter means between 1799 and 1820. In 20 of these 22 winters mean temperature was below average, and in 10 of them the deficit exceeded 2°F.

Fuller details are given in *Climatological Memorandum* No. 41.[2]

REFERENCES

1. Washington, Smithsonian Institution. World Weather Records. *Smithson. misc. Coll., Washington D.C.*, **90**, 1934, p. 23 and p. 511.

2. THOMSON, A. B.; Mean winter temperature in Edinburgh: 1764/65–1962/63. *Met. Off. clim. Memor., London*, No. 41, 1964, (unpublished, available from the Meteorological Office).

METEOROLOGICAL OFFICE DISCUSSION

Developments in meteorological instrumentation

The Monday Discussion held on 16 December 1963 at the Royal Society of Arts was concerned with developments in meteorological instrumentation and the opening speaker was Mr. C. E. Goodison. He described two groups of instruments which were either in production or being developed.

The first production instrument he dealt with was the cloud base recorder five of which have been in operation for 2½ years. This instrument is a modulated light ceilometer which has been developed by the Meteorological Office and is designed to give cloud height from 50 to 4000 feet. There are two airfield units; these are a transmitting searchlight, and a photo-electric cell receiver which has a 900 c/sec tuned amplifier associated with it and combined in the same case. In the office a recording unit with strip-chart mechanism maintains a record of the cloud base. (See Plates I–III.)

A brief description of a manufactured photo-electric visibility meter, was then given, accompanied by some slides showing the installation at the Meteorological Experimental Site near Bracknell.

The new radar equipments—wind-finders and weather surveillance types—which are shortly to be introduced into meteorological service, were then discussed. The wind-finding set is a 10-cm 800-kw equipment which will replace the war-time G.L. radars in use on radiosonde stations. It is capable of automatically following a Met.O Mk.3 target to 200 km and because of extensive use of transistors in the design should prove to have good electronic reliability.

There are two types of weather radar about to be installed at various sites around the world. The Public Weather Centres at home will be supplied with 3-cm sets which should enable the forecaster to watch the progress of precipitation through his area of immediate responsibility. These 3-cm sets are of relatively simple construction and they should be easily operated and serviced and give the minimum of trouble.

The 10-cm weather radar sets will be installed in tropical areas where they should prove a boon to the research branches as well as a good aid to the local forecaster.

There are 15 data loggers of quite advanced design in the Office at present and these will present records of various radiation parameters in two ways, viz. a multi-trace pen recording chart and a punched paper tape. These data loggers will be sited at home and overseas and trial installations of the equipment are also at present being carried out on Ocean Weather Ships.

The last production piece of equipment demonstrated was an electro-mechanical device for sending meteorological messages automatically. There are 69 switches in front of the instrument and after setting these up to the required message all that is then necessary to send the message at full teleprinter speed is to push a button. In the demonstration a teleprinter connected to the automatic message sender printed the message when the 'transmit' button was operated.

A few instruments in the course of development were then described and the automatic weather station (AWS) was the first subject to be discussed. At

an early stage of development the project was divided into two parts. It was decided that the telemetry equipment would be the subject of a specification and contract so that it would 'marry up' well with the transducers which were to be developed by the Office.

The telemetering equipment has now been delivered by the makers. Various slides showing different aspects of it were then shown and a brief description of its characteristics given. Its ability to be interrogated over an ordinary subscriber's line is a most important point since a private wire connexion would be most uneconomical in the role which is foreseen for AWS in the British Isles.

The transducers, which produce an electrical signal in the form of voltages, were the responsibility of the Office and models of them have been built capable of measuring barometric pressure, mean wind speed, wind direction, dry-bulb temperature, wet-bulb depression, total rainfall, rate of rainfall, presence of bright sunshine, and visibility. The details of these nine transducer models were then given with accompanying slides. (See Plate IV.)

Another instrument which was on display but not completely demonstrated was the receiving cabinet of a digital display AWS. This type of station was designed with large airfields in mind where it is difficult to obtain good instrument exposure near the forecast office. By using this version of the AWS which only uses one pair of GPO wires, instruments at a distance of up to 10 miles may be interrogated individually and their readings displayed in a digital form complete with units, e.g. 1015 mb, 15.1°C etc. This instrument was designed and built completely by the Office and also uses the same transducers as the AWS.

The last instrument system Mr. Goodison described was a new type of satellite cloud-cover picture transmission. The previous TIROS satellites had various limitations on their performance, one of the principal barriers being that of communication between the satellite and the forecaster. This link at present is a long and tortuous one involving tape recorders in the satellite, specially equipped ground stations in North America, rectification procedures, and the ordinary meteorological communication channels. Because of this delay, pictures useful to the forecaster may be delayed by up to 24 hours. The 'automatic picture transmission' (APT) equipment, which will be carried by future meteorological satellites, broadcasts each picture by radio immediately after it has been taken. This means that any meteorological organization equipped with a fairly elementary ground receiving station will be able to have satellite cloud-cover pictures almost as soon as they are taken. The Meteorological Office is at present investigating the possibility of producing a Met.O. designed ground station to receive these APT signals from satellites.

One of the principal speakers in the discussion was Mr. V. R. Coles (Assistant Director Met.O. (Central Forecasting)) who described an automatic chart plotter which was being produced for Met.O.2. This illustration brought a comment on its international acceptability. Various points on the instruments shown were discussed and whilst it was agreed that electronics had advanced automatic observing techniques some basic problems still remained, such as the maintenance of a clean wick on the wet-bulb thermometer.

The Director-General wound up the discussion by emphasizing that the instrument revolution was only of comparatively recent origin and that Robert Hooke who set up the first meteorological observing station in the 17th century would have had no difficulty in recognizing all instruments in use in the thirties whereas the equipment with which a modern meteorological office was furnished would be quite foreign to him.

REVIEWS

An introduction to the hydrodynamical methods of short period weather forecasting, by I. A. Kibel', (translated from the Russian). Edited by R. Baker. $9\frac{1}{4}$ in $\times$ 6 in, pp. xiii + 383, *illus.*, Pergamon Press Ltd., Headington Hill Hall, Oxford, 1963. Price £5.

Dr. Kibel' wrote a well known paper in 1940 in which he derived formulae for predicting the motion of pressure centres and so may be regarded as having given fresh impetus in Russia to the study of what is now called numerical weather prediction. Since then he has been the inspirer of the many Russian meteorologists who have carried out research work on numerical weather prediction and has himself contributed significantly. A text book written by such a great expert in this field can only be welcome.

The basis of the book is a series of University lectures given by the author in 1956 and the text was first published in Moscow in 1957. Dr. Kibel' may thus be regarded as the author of the first text book dealing adequately with the recent advances in applying hydrodynamics and computing methods to predicting the behaviour of the atmosphere. It is a pity that the English translation has had to be so long delayed for there have been considerable advances since Dr. Kibel' wrote his book; however in a field in which progress is rapid any text is likely to appear out-dated within a few years and since there is no other book which covers the ground in the same detailed way, Dr. Kibel''s book remains the most authoritative, in English as well as in Russian.

Somewhat naturally there is a distinctly Russian flavour about the contents and indeed the author indicates that the foreign work is described mainly by its computed results while the theoretical Russian work is described in detail; at the same time it is clear that he has a wide and up-to-date knowledge of the parallel research work which was being carried out elsewhere in Europe and America. It is surprising that the research during these formative years should have been so similar and that the same ideas were being investigated in both the East and West. There are notable differences, especially in technique, but these should not mask the similarity of the physical ideas lying behind the mathematical equations that form the basis of the arithmetical computations. The difficulty of making a comprehensive survey was thus reduced and Dr. Kibel' has been able to deal with both aspects in a coherent whole. The Russian research work in particular was aimed at a systematic examination of the quasi-geostrophic vorticity approach to the problem of using the hydrodynamical equations for prediction and that is the essence of this book.

Throughout the book there is a note of formality which we associate with a university text in mathematical physics and which ensures a logical development; this may seem rather painstaking at times but it is pedagogically desirable.

The first two chapters are concerned with laying the foundations—the thermal physics of the boundary layer expressed in mathematical terms and the equations of motion in the free atmosphere in hydrostatic equilibrium. All of this is very carefully set out and the calculations, such as that of the change from cartesian to pressure co-ordinates, carried out in detail. The third chapter is the important one which gives the orders of magnitude of the various terms which arise in the equations when synoptic-scale motions are considered; this of course is vital for the subsequent development and is carefully written. Dr. Kibel′ might now not be so decided in his view that the tendency equation cannot be used to estimate pressure changes with time in view of more recent work using the primitive equations.

Having laid the foundations in these early chapters, the main interest lies in Chapters 4, 7, 8 and 9 which present the non-linear problem and its solution for both a single-layered fluid and a multi-layered one. The Russian approach to the problem is to formulate a single differential equation giving the height tendency in terms of the horizontal and pressure derivatives of the contour heights and to solve this equation under suitable boundary conditions. The solution is generally given in terms of an integration which involves as a weighting factor the Green's function for the problem and its boundary conditions. The crux of the problem is to find an expression for the Green's function. In principle when this is done the problem is solved; in practice the integrations have to be carried out in the simple manner of replacing them by sums. The approach more familiar to us is to concentrate on simple models right from the start, obtain sets of simultaneous differential equations which are simpler to manipulate and use finite difference techniques which do not require the construction of a Green's function. Both methods are given but the details are confined to the Green's function method; both require a great deal of computation on an electronic computer and it is not clear which is the more economic. Dr. Kibel′ gives examples of forecasts computed by different methods but since the different computations do not refer to the same dates it is not possible to assert that any method is superior to another.

There are other chapters concerned with linearized models, frontal zones and the introduction of the physical boundary effects into the computations and they maintain the same high standard. This standard has not been maintained editorially in the English translation for there are many minor errors and infelicities of expression. There are irritating mis-spellings of names, such as Gilbert for Hilbert, which should have been checked, the residual at a point is never called the discrepancy and the mathematics in the original Russian had less errors than has the translation. One point in favour of the translation is that an index has been added.

This is an excellent and valuable text which dynamical meteorologists will welcome as an exposition of the basic physical ideas behind numerical prediction and the research carried out, as seen in 1956; perhaps a rather different book would be written in 1964.

E. KNIGHTING

Die Faxfibel, by Dr. Martin Rodewald. 9½ in × 8¼ in, pp. 71, illus., Dr. -Ing. Rudolf Hell, 23 Kiel, Grenzstrasse 1–5, 1963.

"What the seaman must know about weather charts" is the title of a primer on the use of weather charts such as are broadcast by many countries nowadays as facsimile reproductions of the charts drawn in a meteorological office.

The book is simply written by an experienced meteorologist, Dr. Rodewald, belonging to the German marine weather service at Hamburg. After introducing the international weather symbols used on weather charts, the author shows how wind can be estimated from the pressure field, and gives a nomogram which includes allowance for curvature of isobars. Another chapter deals with the main frontal systems, illustrating among other things 'wave' development on a front, and the weather and wind associated with fronts.

One of the features of the book is the high standard of the reproduction of the numerous charts and diagrams, and the care shown in the author's choice of material to illustrate various parts of the text. Typical tracks of depressions and anticyclones are shown as well as tracks of tropical storms. The use of certain special charts is explained, with examples of forecast charts, upper wind charts, sea and swell charts and ice charts.

Some of the more general rule of thumb methods of forecasting are given, as well as rules applicable to special weather situations and for forecasting developments—all well chosen examples, though mainly in the German forecasting tradition.

Finally some types of persistent weather patterns are illustrated for the North Atlantic and, as is reasonable in a book for seamen, a few types are also given for the Mediterranean, Gulf of Mexico, Arabian Sea and the Far East.

The booklet deserves a wide public though apparently issued primarily as advertising material to encourage shipowners to install a particular make of Facsimile apparatus whose development and operation are described in an appendix.

W. S. G.

HONOUR

We note with pleasure the election of Professor P. A. Sheppard, C.B.E. as Fellow of the Royal Society on 19 March 1964.

OFFICIAL PUBLICATION

The following publication has recently been issued:

Meteorological Glossary, 4th Edition. London, HMSO, 1963. Price 32*s*. 6*d*.

This, the 4th Edition of the Meteorological Glossary has been almost completely rewritten and the opportunity has been taken to include many more items than were contained in the previous editions.

The items include most of the terms and concepts which are in common use in the various branches of meteorology and some others which are less familiar. In addition, relevant information from mathematics, statistics, physics and other branches of geophysics is included.

While emphasis is placed, in certain items, on British terminology, methods and data, much the greater part of the book contains information which is applicable to all parts of the world.

Many of the Figures are new and the 28 Plates now include 8 coloured ones for the first time.

CORRIGENDUM

Meteorological Magazine, March 1964, page 76, line 29: for "30 to 40 °E" read "30 to 40° further east".

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